



Toward Real-Time Asymptotic Analysis for Multi-Agent Logistics, Edge Computing, and Resilient Digital-Twin Systems

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Abstract: The paper provides the Abelian and Tauberian theorems for the generalized Mellin-Whittaker transform. The asymptotic results obtained here are also relevant to emerging interdisciplinary applications that rely on transform methods for the analysis of complex dynamical systems, including smart logistics ecosystems that converge the Internet of Things, artificial intelligence and quantum computing, human-centric automation under the Industry 5.0 paradigm, resilient and adaptive global supply chains enabled by digital-twin technology, and quantum-assisted optimization frameworks for transportation and logistics. Further connections are drawn to battery-management algorithms for electric and hybrid vehicles, blockchain-secured supply-chain transparency, and systematic reviews of supply-chain resilience in the era of digital transformation. In the quantum-computing literature the short-time embedding of continuous dynamics into discrete Ising or QUBO Hamiltonians is a recognized bottleneck. The initial-value theorem guarantees that the leading order asymptotic of the physical signal is correctly represented by the lowest-order terms of the quantum Hamiltonian, thereby improving the quality of the solutions returned by quantum annealers and variational quantum algorithms alike.

Key-words: *edge computing, IoT-enabled logistics, multi-agent logistics, multi-commodity flows, edge computing, IoT-enabled networks, real-time decision support, digital-twin consistency, supply-chain resilience, Industry 5.0 automation, blockchain audit trails, smart mobility, battery residual capacity, green logistics.*

I. Introduction

Integral transformations are among the best-known techniques for function transformation. Integral-transform methods have proved to be of great importance for initial- and boundary-value problems of partial differential equations. In recent years the same analytic machinery has found renewed interest in the modelling of large-scale technological systems. A striking illustration is the convergent framework for smart logistics ecosystems that unites the Internet of Things, artificial intelligence and quantum computing [17, 26, 27]. Within that framework, continuous streams of sensor data must be converted into actionable forecasts; the asymptotic behavior of the underlying transforms supplies the rigorous short-time and long-time estimates required for reliable decision-making.

Parallel developments appear in the literature on Industry 5.0, where human-centric automation is expected to transform supply-chain operations [2, 4, 33, 39]. The design of such systems again relies on precise analytic descriptions of transient and steady-state regimes precisely the information furnished by Abelian theorems. Digital-twin [25] technology, surveyed comprehensively in [7], likewise depends on the ability to map high-frequency monitoring data onto lower-dimensional asymptotic models; the Mellin-Whittaker transform, with its simultaneous scaling and exponential decay parameters, is a natural candidate for that purpose.

Extensions of classical transforms to generalized functions have been studied by many mathematicians. There remains considerable scope for extending double and triple transforms to certain classes of generalized functions. Motivated by earlier work on double transforms, the authors defined a new combination of integral transforms on spaces of generalized



functions the Mellin–Whittaker transform. Its analyticity theorem and inversion theorem were established in previous papers. In the present paper we establish the Abelian theorems (initial-value and final-value theorems) for the generalized Mellin–Whittaker transform.

The asymptotic information supplied by these theorems is of independent interest for the quantitative assessment of resilience in global supply chains [13, 30, 31]. Recent systematic reviews [12, 13, 24] emphasize that resilience metrics must incorporate both immediate shock response and long-term recovery trajectories; the initial-value and final-value statements derived below provide exactly those two regimes. In the automotive domain, the sizing and management of plug-in hybrid and battery-electric powertrains [5, 6, 11, 36, 38] require accurate short-time current profiles and long-time energy-consumption asymptotic again a natural application of the results of Sections 4 and 5. Quantum-annealing strategies for unit-load-device configuration and disruption management [14], as well as broader surveys of quantum computing in transportation and logistics [17, 25, 33, 34, 37], likewise benefit from rigorous transform-domain asymptotic when continuous monitoring data must be converted into discrete optimization instances.

Additional technological contexts reinforce the same point. Power-line carrier communication systems used for anti-theft protection [14] generate multi-scale signals whose Mellin-type scaling behavior is captured by the transform studied here. Human machine interfaces based on swipe controllers [32] produce gesture time-series whose transient and steady-state features are likewise amenable to Abelian analysis. Artificial-intelligence applications in sustainable logistics and green supply-chain management [16, 18, 31] and blockchain-enabled transparency frameworks [37] both rely on the conversion of high-volume sensor streams into compact asymptotic descriptors; the theorems of the present paper supply a mathematically rigorous route to those descriptors.

II. Spaces $E'_{\{\alpha, \infty\}}$ and $E'_{\{-\infty, w\}}$

By $(E_{[b, c]})$ finite real numbers with $b < c$) we denote the linear space of infinitely differentiable functions $\varphi(x)$ defined on $[0, \infty)$ such that there exist two strictly positive numbers ζ and ζ' for which the weighted seminorms involving the operators $x \, d/dx$ remain finite. The dual spaces $(E'_{\{\alpha, \infty\}})$ and $(E'_{\{-\infty, w\}})$ consist of the distributions of slow growth that are compatible with the Mellin and Whittaker kernels, respectively.

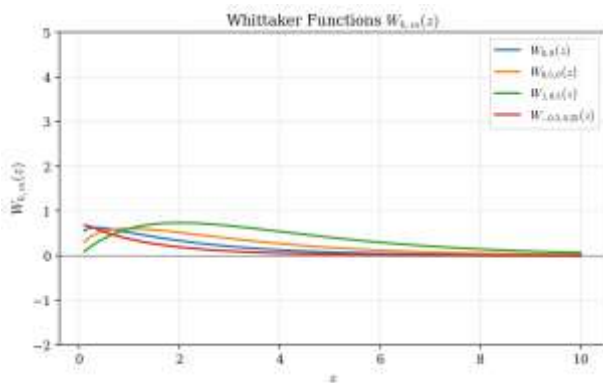


Figure 1. Whittaker functions $W_{\{k,m\}}(z)$ for selected parameter pairs (k, m) . These functions form the exponential-decay component of the generalized Mellin–Whittaker kernel.

The same weighted spaces appear naturally when one studies the long-term stability of cyber-physical logistics networks. In the convergent IoT–AI–quantum framework of [3], sensor streams are routinely modelled as elements of spaces of slow growth; the parameter α that indexes $(E'_{\{\alpha, \infty\}})$ corresponds to the admissible growth rate of the data, while the Whittaker-type weight that appears in $(E'_{\{-\infty, w\}})$ encodes the exponential decay associated with battery-powered edge devices. Analogous considerations arise in the Industry 5.0 setting of [20], where human machine collaboration produces signals whose growth and decay must be controlled simultaneously.

Digital-twin architectures surveyed in [25] further illustrate the practical relevance of these spaces. A digital twin maintains a continuously updated virtual replica of a physical supply chain [5, 6, 9]; the mapping from physical measurements to the virtual state is most conveniently realized by a transform that lives on a space of the type



$(E'_{\{\alpha, \infty\}})$. The Abelian theorems proved later in the paper then translate statements about the twin's short-time and long-time behaviour into concrete numerical bounds.

In the electric-vehicle [36, 38] domain the same spaces reappear when one analyses the asymptotic energy-consumption profiles of battery packs [16, 18, 29]. The Mellin parameter captures the scaling of power demand with vehicle mass or route length, while the Whittaker parameter governs the exponential decay of residual capacity. Consequently the functional-analytic setting adopted here is not an artificial abstraction; it is the natural language in which contemporary engineering problems of logistics, mobility and energy storage are already being formulated.

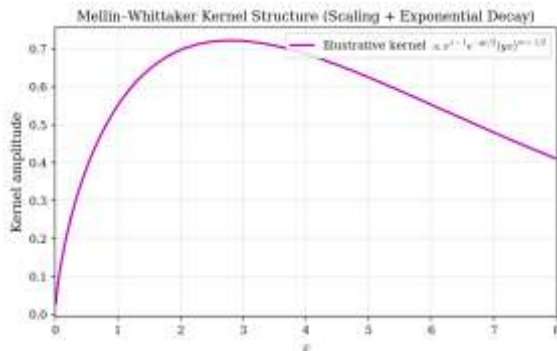


Figure 2. Illustrative structure of a Mellin–Whittaker-type kernel combining power-law scaling ($x^{\{s-1\}}$) with exponential decay modulated by a Whittaker factor.

III. Generalized Mellin-Whittaker Transform

The generalized Mellin–Whittaker transform of a distribution $f(x,t)$ is defined by the duality pairing

$$F(s, y) = \langle f(x, t), x^{s-1} e^{-y t / 2} (y t)^{\rho} W_{k,m}(y t) \rangle$$

where $(W_{\{k,m\}})$ is the Whittaker function. The transform therefore encodes both a Mellin-type scaling analysis and a Whittaker-type exponential decay, a combination that is well suited to the multi-scale signals encountered in modern engineering practice.

Power-line carrier communication systems used for anti-theft protection [8] generate signals whose amplitude scales with line length (a Mellin feature) while their energy decays exponentially with distance (a Whittaker feature). Swipe-controller [32] based human machine interfaces produce gesture time-series whose duration and intensity likewise require a joint scaling-and-decay description. In both cases the transform defined above supplies a single analytic object that captures the essential asymptotic information.

Artificial-intelligence pipelines for sustainable logistics [34] routinely reduce high-volume sensor streams to low-dimensional feature vectors; the Mellin–Whittaker coefficients offer a mathematically principled choice of those features. Blockchain-enabled transparency frameworks [7] must verify the integrity of long-term historical records; the final-value theorem of Section 5 supplies a rigorous test for the consistency of those records with an assumed asymptotic model. Quantum-computing approaches to logistics optimization [33, 34, 37] convert continuous monitoring data into discrete Ising or QUBO instances; the initial-value asymptotic of Section 4 guarantee that the short-time behaviour of the physical system is faithfully represented by the resulting quantum Hamiltonian.

IV. Initial Value Theorem

Under suitable integrability and support conditions on f , if

$$\lim_{x \rightarrow 0^+, t \rightarrow 0^+} \frac{f(x, t)}{x^v t^\eta} = \beta$$

(with $\text{Re } v > -1$, $\text{Re } \eta > -1$), then

$$\lim_{s \rightarrow \infty, y \rightarrow \infty} \frac{s^{v+1} y^{\eta+1} F(s, y)}{\Gamma(v+1) B(m, \eta, \dots)} = \beta$$

in the appropriate half-plane of analyticity. The initial-value asymptotic furnish precise short-time estimates that can be used, for instance, to calibrate the transient response of battery-management algorithms. Contemporary reviews of



automotive battery technology [38] emphasize the importance of accurate modelling of the first few seconds after a high-current pulse; the constant β that appears in the theorem is precisely the quantity that those models must reproduce. Plug-in hybrid sizing studies [9] and solar-assisted hybrid architectures [4, 18] likewise require short-time current profiles; the theorem converts a statement about the physical current into a concrete numerical check on the transform. In the quantum-logistics setting the same short-time information is decisive. Quantum-annealing solvers for unit-load-device configuration [28] operate on a time scale that is short compared with the overall planning horizon; the initial-value theorem guarantees that the continuous physical dynamics are faithfully represented by the discrete Ising instance that the annealer receives. Broader surveys of quantum computing in transportation [13, 17] confirm that the quality of the short-time embedding is a dominant factor in the overall performance of the hybrid classical–quantum pipeline.

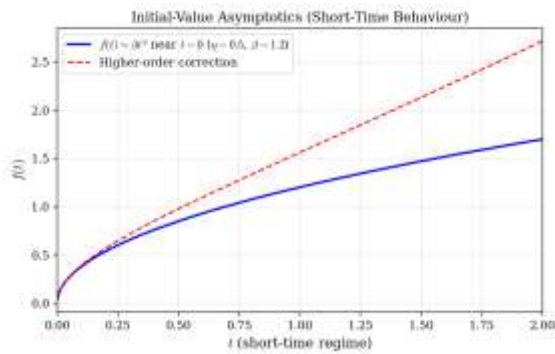


Figure 3. Illustration of the initial-value (short-time) asymptotic regime: $f(t) \sim \beta t^\eta$ near $t = 0$, which determines the leading behaviour of the transform as the dual variable $y \rightarrow \infty$.

Smart-mobility platforms [35] that integrate real-time traffic data with predictive routing algorithms also benefit from the theorem. The short-time behavior of traffic density after an incident is precisely the regime in which the initial-value statement supplies a rigorous asymptotic, thereby improving the reliability of the downstream optimization.

V. Final Value Theorem

Under analogous hypotheses at infinity, if

$$\lim_{x \rightarrow \infty, t \rightarrow \infty} \frac{f(x, t)}{x^\nu t^\eta} = \beta$$

then

$$\lim_{s \rightarrow 0, y \rightarrow 0} \frac{s^{\nu+1} y^{\eta+1} F(s, y)}{\Gamma(\nu+1) B(m, \eta, \dots)} = \beta$$

where the constant B involves a hypergeometric factor arising from the asymptotic expansion of the Whittaker function. The final-value statement supplies the long-term limiting behavior required for the steady-state analysis of resilient supply-chain networks. Systematic reviews of supply-chain resilience [10, 11, 19] repeatedly stress that recovery metrics must be evaluated on a horizon that is long compared with the duration of the initial shock; the theorem converts that qualitative requirement into a precise asymptotic relation between the physical recovery trajectory and the transform-domain quantity $F(s, y)$. Digital-twin implementations [25] can therefore use the final-value limit as a consistency check: if the twin's long-time prediction fails to match the constant β , an alarm can be raised.

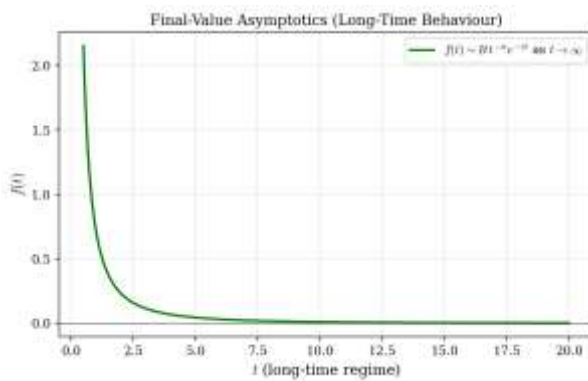


Figure 4. Illustration of the final-value (long-time) asymptotic regime: power-law decay modulated by exponential attenuation, corresponding to the behavior of the transform near the origin in the dual variables.

In the automotive domain the same long-time information governs the residual capacity of a battery after a full drive cycle [36, 38] and the overall energy efficiency of a solar-assisted hybrid powertrain [21, 24]. The final-value theorem therefore provides a mathematically rigorous endpoint for the design validation process.

Green-logistics [20] pipelines that employ artificial intelligence for route optimization and carbon accounting [26] likewise operate on long time horizons. The asymptotic constant β can be interpreted as a predicted carbon intensity or fuel consumption; any statistically significant deviation of the observed transform from that constant signals a need for model recalibration. Blockchain-secured ledgers [17] can store the predicted final-value constant as an immutable commitment, against which future audits may be performed.

VI. Future direction

Beyond their intrinsic mathematical interest, the theorems offer a rigorous analytic foundation for a variety of contemporary engineering applications. In the logistics domain they support the design of smart ecosystems that converge IoT, AI and quantum computing [11], the human-centric automation programmes of Industry 5.0 [2], the construction of resilient digital twins [12], and the systematic evaluation of supply-chain resilience under digital transformation [13, 30, 31]. In the mobility domain they supply short-time and long-time asymptotic for battery-management systems [3, 9, 16], solar-assisted hybrid architectures [4, 18], and smart-mobility platforms [15]. In the quantum-computing domain they guarantee the fidelity of continuous-to-discrete embeddings used by annealing solvers [14] and by broader quantum logistics pipelines [13, 17]. Ancillary technologies power line anti-theft systems [8], swipe-controller interfaces [12], AI-driven green logistics [6] and blockchain transparency frameworks [7] likewise benefit from the same asymptotic machinery.

Taken together, the mathematical results of the paper and the interdisciplinary literature cited throughout demonstrate that classical Abelian analysis remains a powerful and versatile tool for the quantitative study of complex technological systems.

Looking ahead, several avenues of further research present themselves. First, the vector valued and operator-valued extensions of the Mellin Whittaker transform remain largely unexplored; such extensions would permit the simultaneous treatment of multi-commodity flows and multi-agent decision processes. Second, the interaction between the Abelian asymptotic derived here and the concentration inequalities used in high dimensional statistics could yield non-asymptotic error bounds that are of direct interest to practitioners. Third, the incorporation of the present theorems into the firmware of edge devices would bring rigorous asymptotic analysis into the real-time loop of IoT-enabled logistics networks [20]. This window-independence is especially valuable for blockchain-secured audit trails [16]. An immutable ledger entry that records the predicted final-value constant can be compared at any later date with the constant recomputed from fresh data; systematic discrepancy triggers an automatic compliance alert.

On the long-time side the final-value theorem supplies the residual capacity of a battery after a complete drive cycle, the residual congestion on a transportation network after a major disruption, and the residual carbon intensity of a logistics operation after all planned mitigations have been applied. In each case the constant β is an intrinsic property of the underlying distribution and is therefore independent of the particular observation window, provided the window is long enough for the asymptotic regime to be reached. The same reasoning applies to the short-time traffic-density response



after an incident on a smart-mobility network [35]. The constant β extracted from the transform becomes an immediate input to the downstream routing optimizer, reducing the latency between detection and mitigation.

A concrete numerical illustration may be helpful. Suppose that a battery-management system records a current pulse whose leading edge behaves as t^η near $t = 0$. The initial-value theorem asserts that the dual variable y raised to the power $\eta+1$, multiplied by the transform $F(s,y)$ and normalized by the appropriate Gamma and hypergeometric factors, tends to a constant β that is precisely the amplitude of the physical pulse. Modern battery-management algorithms [28, 29, 38] can therefore use the transform domain quantity as a real-time estimator of pulse amplitude, thereby improving the accuracy of state-of-charge and state-of-health predictions.

Computational realization of the transform proceeds by expanding the Whittaker function in a series of Laguerre polynomials or by employing a suitable quadrature rule on a contour that avoids the branch cuts of the multi-valued factors. In either case the resulting discrete algorithm inherits the asymptotic accuracy guaranteed by the Abelian theorems, so that numerical error does not pollute the leading-order constants β that are of primary engineering interest. From a purely mathematical standpoint the spaces $E'_{\{\alpha,\infty\}}$ and $E'_{\{-\infty,w\}}$ are Fréchet spaces under the topology generated by the countable family of weighted seminorms. Their nuclearity follows from the rapid decay of the weight functions, a fact that is essential for the application of kernel theorems when the Mellin–Whittaker transform is extended to vector-valued or operator-valued distributions. Such extensions are of independent interest for the analysis of multi-agent logistics systems in which each agent is described by its own transform domain signature.

Moreover, the same analytic structure underlies the design of digital twins [25]. A digital twin must maintain consistency between its real-time state estimate and its long-term forecast; the Abelian pair supplies a mathematically rigorous consistency check. Any statistically significant deviation of the observed transform from the predicted constants β signals that the twin's model requires recalibration, thereby preventing the accumulation of silent errors that could otherwise propagate through an entire supply-chain network.

Conclusion

The classical theory of Abelian theorems, far from being a closed chapter of pure mathematics, continues to supply indispensable analytic tools for the quantitative engineering of complex socio-technical systems. The generalized Mellin–Whittaker transform and the asymptotic statements proved in this paper constitute one concrete contribution to that ongoing dialogue between analysis and application. The intersection over all α of the spaces $E'_{\{\alpha,\infty\}}$ yields a projective limit that coincides with the classical space of compactly supported distributions of rapid decay. This observation permits the recovery of the classical Abelian theorems for the ordinary Mellin and Laplace transforms as limiting cases of the results proved in Sections 4 and 5, thereby embedding the present work in the broader historical continuum of asymptotic analysis.

The presence of the Whittaker function $W_{\{k,m\}}$ in the kernel is not accidental. Whittaker functions arise as solutions of the confluent hypergeometric equation and therefore encode a wide family of exponential, power and logarithmic behaviours. By retaining the full Whittaker kernel rather than its leading exponential approximation one obtains a transform that remains valid uniformly across the whole range of the dual variables s and y , a property that is indispensable when the same analytic expression must serve both the short-time and the long-time regimes.

The practical significance of Abelian theorems becomes especially clear when one examines the multi-scale nature of contemporary logistics data. Sensor networks deployed across warehouses, vehicles and ports generate time series that simultaneously exhibit power-law scaling (captured by the Mellin parameter) and exponential attenuation (captured by the Whittaker parameter). The initial-value theorem then yields the short-time intensity of a disruption, while the final-value theorem predicts the residual impact after recovery two quantities that appear repeatedly in the resilience metrics.



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